

Comparisons of Different Gamma Ray Generation Scenarios

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Abstract. Contemporarily, gamma photons have been implemented in various application on account of its unique features. In this paper, the basic physical properties of gamma ray are introduced with its advantages and disadvantages in multidisciplinary applications. For the sake of comparison so as to find the most efficient way to generate the gamma rays, the advanced schemes are selected to estimate. To be specific, the historical developments including the discovery of gamma ray and its explanation in the framework of Compton's Effect are discussed in detail. In addition, the prevalent mechanisms behind artificially-produced gamma-ray are covered and demonstrated, among which the free- electron laser (FEL) and the laser-plasma interactions based on the state-of-art high power laser systems are compared with respect to the properties of the gamma-rays produced. According to the analysis, the resourced input, and their respective advantages in the evolution of gamma-ray production industry are evaluated. Overall, these results shed light on guiding further exploration of gamma ray generation based on various scenarios.

Keywords: Gamma-ray; Free-electron Laser; Laser-plasma Interaction; Comparison.

1. Introduction

Gamma rays, having highest frequencies (i.e., the largest photon energy) among all electromagnetic waves on the light photic spectrum, are able to transmit the largest amount of energy given identical beam intensities. Naturally, they can be produced only by the most violent and energy-concentrated activities within the universe (e.g., collisions of fast-spinning neutron stars), the explosions of supernovas, and the absorptions of mega-mass celestial bodies by the black holes [1]. Identified as a new type of radiation by Ernest Rutherford with the highest penetrating abilities hitherto, gamma ray's generation is accounted by the periodic decay of the nuclei of radiative atom, and great potentials have been shown about its outstanding piercing abilities in multidisciplinary applications.

One major use of gamma rays concerns the elimination of specific organisms. In oncological treatment, the gamma rays can remove abnormal tissues effectively given prolonged exposure in a process known as irradiation. One popular application is the removal of malignant tissues, in which the operations can be performed with higher flexibility compared with scalpel-based ones, given the small size and appropriate orientation of the laser emitter and the stability of ray paths [2]. While such treatments are immediately effective in normal cases, the side effects are also prominent, whereby benign tissues in the bodies undergo an indiscriminate elimination that may result in weakened immunity system. Despite the ongoing researches into special radiative shielding materials (e.g., the tungsten carbide) that prevents the rays from reaching non-targeted areas [3], improvement on the accuracy of radiative treatment is also of necessity. The side-effect of tumor elimination, for instance, would be significantly attenuated given a more precise disposition of the rays, thus the target organisms are killed without damages to its benign vicinities. Another application is the maintenance of sophisticated medical instruments. With the ability to pass through solid structure and transmit its high energy with ease, the gamma radiation turns out extremely useful in sterilization, whereby the DNAs of microorganisms such as bacteria and viruses are broken in gamma-penetration. This further leads to disorganization of biological mechanisms and eventually kills the targets.

In the field of nanotechnology, gamma-rays are likely useful. One widely acknowledged instance will be Molybdenum trioxide [4], whose conductivity is shown to be an attraction in a variety of applications. Specifically, by employing the irradiation of ^{60}Co gamma ray, it is possible to modify the material's optical properties and Urbach energy as needed [5]. Further, a study in the past decade

has demonstrated gamma-ray's potentials in protecting communities. This particular type of gamma rays is generated through Laser Compton Scattered Effects, and can be utilized in nondestructive detection of nuclear materials [6] and the identification of nuclides (by the nuclear resonance fluorescence, a photo reaction of specific-isotope), thus providing aids for tracking illegal-transported nuclear materials. Considering gamma rays' multifaceted utilities, it is necessary that investigations be conducted into how to maximize the benefits of its uses in different application cases by improving the mechanisms to produce gamma radiations. According to the formula for inverse Compton Effect [7]:

$$\hbar\omega' = \gamma\hbar\omega \left(1 + \frac{v}{c} \cos\theta\right), \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \quad (1)$$

the maximum energy of the scattered photon is proportion to the relativistic energy of the collided electron, and inversely so to the angle between the desired scattering direction and the actual one. To accelerate an electron as to attain enormous relativistic kinetic energy for the inverse Compton Effect to take place, one possibility is ultrahigh laser, specially, the high-power laser-plasma interactions. In this process, a laser beam of high intensity is emitted and collides with a gas plume consisting of helium (with a proportion of a few millimeters for the radius), and from this interaction arises beams of electron that are highly charged [8], which proceed to transmit through the bremsstrahlung converter that produces gamma rays and electron beams based on the Inverse Compton Effect. This admixture then comes under the influence of a permanent magnetic field that reorients the beams of electrons within and thus functions as a filter for the desired gamma rays.

The second way to produce gamma rays is by the interactions between a beam of relativistic electrons and a laser wiggler of miniscule proportion. Gamma rays produced in this way has been exclusively characterized by a high degree of polarization, excellent directionality, high intensity, and good collimation, which makes it way more qualified in the cases of nuclear physics researches in comparison with gamma rays produced in alternative ways [9]. The major experimental set-up for this approach consists of a storage ring, in which two bunches of electrons (typically separated by half of the storage ring's circumference) continuously circulate. Two undulators generating magnetic fields of equal intensity but different helicities are also installed, which force the by-passing beam of electron to oscillate periodically, thus producing the free electron laser (FEL). Once the laser is generated by one of two electron beams, collisions will take place between the FEL and the other one, which gives rise to gamma ray in one direction along the line of the two undulators during the Compton Scattering. Furthermore, the second beam of electrons will similarly emit a FEL after the collision, which in turn collides with the first one and generates a second gamma ray in opposite direction of the first one, thus forming a circle [10].

The motivation of this paper is to compare systematically the characteristics, including advantages and shortages, of two major approaches for gamma-production nowadays, i.e., the laser-plasma interactions and the free-electron laser (FEL). Conclusions drawn from specific aspects about these two approaches may be contributory in the improvement of future production mechanisms. This paper is majorly divided into the following parts. The Sec. 2 will give the basic description of laser-plasma and interactions as well as the introductio of FEL. Subsequently, the Sec. 3 will compare the two scenarios in detail. Eventually, a brief summary will be given in Sec. 4.

2. Basic description of Laser-plasma Interactions and FEL

2.1. Laser-plasma Interactions

The experimental set-up of a typical laser-plasma accelerator includes gas jet, which is expected to experience violent implosion after being hit by a laser beam and gives rise to ultrahigh rays of electrons. These beams, generally consisting of relativistic electrons with enormous kinetic energy, proceed to interact with bremsstrahlung converter where deceleration takes place with a considerable

amount of energy transformed into electromagnetic waves by the Compton Scattering. In the end, a permanent magnet is installed so as to filter the neutral, targeted waves from the charged ones as shown in Fig. 1.

Comprehensive researches have been done in order to find the parameters in gamma ray production by laser-plasma interactions. To obtain ultrahigh beams of electrons, the inertial confinement fusion (ICF) is triggered using laser rays to implode the gas jet, where a small amount of nuclear material is included within a capsule of miniscule proportion (usually a millimeter in size) [11]. To maximize the energy of the resultant electron beams, so that a source of gamma ray of higher intensity can be produced subsequently by the deceleration of charged electrons during bremsstrahlung, the implosion needs to be magnified, which is triggered by heat generated during the laser absorption into a corona of plasma that surrounds the capsule. In this course, a variety of second processes are caused during the propagation of laser beams within the plasma, which reduces the absorption efficiency. One instance is identified as the cross-beam energy transfer (CBET), which is capable of a decrease of laser absorption by 10% to 20%. To mitigate the impact of CBET, experiments were conducted and showed that a decrease in the diameter by 20 % of laser beam will increase the absorption efficiency by 15% [12].

The next key component for the laser-plasma interactions is the bremsstrahlung conductor (also called the target). According to the Inverse Compton Effect, photons of high frequency are produced from lost kinetic energy of the charged electrons within the beam, which hints at the necessity of heightening the conversion efficiency by adopting a conductor that can decelerate the by-passing electrons to the largest extent so that more kinetic energy can be transformed. So far, investigations have shown that an optimization of the geometrical properties of the bremsstrahlung, or the target, is profoundly important in increasing the conversion efficiency. It has been demonstrated that by the adoption of a front-surface target shaped into towers, flat, and slabs, the efficiency is able to reach 1.5%, 5.2%, and 7.9% respectively to produce relativistic electrons whose energies exceed 50MeV [13]. Moreover, past experiments have indicated an increase in both the radius and the thickness of a converter is able to result in an approximately linear growth of conversion efficiency to as high as 80% for a gamma source of 100 picometers, even though the produced gamma rays are more likely to have more divergence rather than be concentrated in a particular direction [14]. After the conversion in the bremsstrahlung converter, the resultant mix of electron beams and gamma rays travel under the influence of a permanent magnetic field, which causes the negatively charged electron beams to divert by the Lorentz Force and is effective in separating the two types of rays.

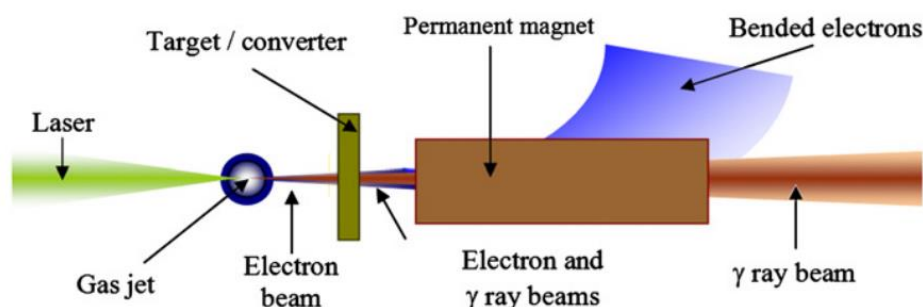


Fig. 1 Illustration of the experimental-setup of Laser-plasma interactions

2.2. FEL

The second way to produce gamma rays is by the interactions between a beam of relativistic electrons and a laser wiggler of miniscule proportion. The major experimental set-up for this approach consists of a storage ring, in which two bunches of electrons (typically separated by half of the storage ring's circumference) continuously circulate. Two undulators generating magnetic fields of equal intensity but different helicities are also installed, which force the by-passing beam of electron to oscillate periodically, thus producing the free electron laser (FEL) beams [15]. Once the laser is generated by one of two electron beams, collisions will take place between the FEL and the other one,

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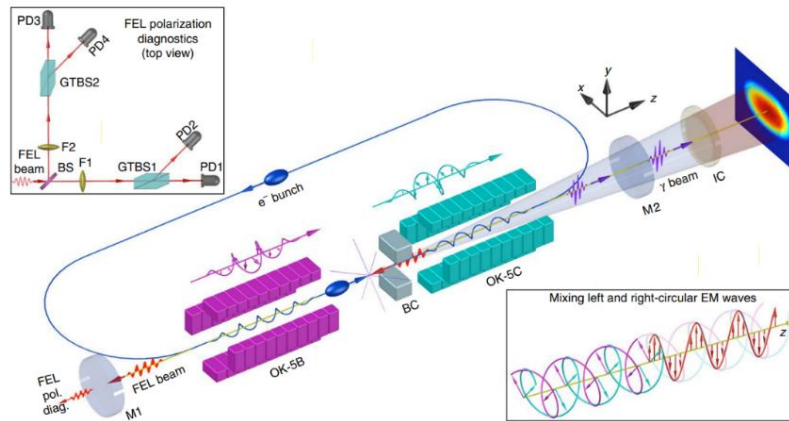


Fig. 2 A sketch of the gamma ray generation based on FEL.

2.2.1 Undulator and advantages of FEL over conventional Lase

In the experimental set-up above, the two undulators are primarily responsible for the energy modulation of electron beams. An undulator basically consists of two parallel series of permanent magnets in straight-line configuration and of equal length; for a specific length along the lines, the magnets on these two lines, respectively, constitute a pair which exert a force tangential to velocity vector of the by-passing particles, causing their trajectories to divert in the direction of one series of magnets. Furthermore, two contiguous pairs of magnets produce a diverting force equal in magnitude but opposite in direction, which cause the diverted electrons to approach the other series of magnets while travelling through. The ultimate result is a beam of electrons travelling in an oscillatory path between the two lines of magnets, or the undulator. The mechanism is presented in Fig. 3. Another key component of the it is an input electromagnetic wave which travel through the undulator together with the electron beam. By making proper adjustments to the intensity of magnetic fields, it is possible to produce a specific oscillation pattern for the electron beam such that the movement of the particles are corresponding to the crest and the trough of electromagnetic waves. The result of the electron oscillation is that the external wave is significantly amplified at the expense of kinetic energy of the electrons in a process known as Self Amplified Spontaneous Emission (SASE) [16].

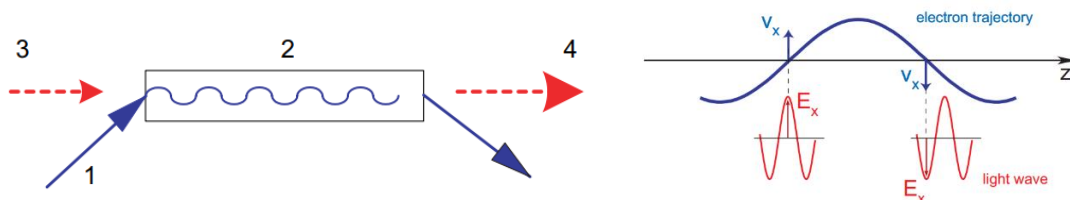


Fig. 3 Undulators mechanism.

In conventional laser, it is possible that the undulation of different travelling particles is independent, which produces radiations scattered into a range of angles as opposed to concentrated in a particular direction. For a beam consisting of specific number of electrons going through the undulator, the total radiation power is the sum-up of that of each electron. In the case of FEL, however, a mechanism is installed whereby it is accessible to collimate the emission of all electron radiation. In this case, the relativistic electrons will travel in beams replace those bound by a medium, usually an atom lie in an optical cavity. On this basis, they are able to travel in vacuum, hence the final radiation becomes coherent and highly intensified compared with its counterpart in conventional accelerator.

2.2.2 General Characteristics

FELs based on this mechanism have flexibility over its laser properties given appropriate adjustment to the parameters of the undulators, including the magnitude of magnetic fields (which determines the frequency of the resultant laser), the peak power, the period length of changes in the directions of the magnetic fields, and the polarization setting. The storage rings, on the other hand, allow the beam of electron to maintain its kinetic energy during circulation, and spatially support its collision with the FEL generated in undulators. Gamma rays produced in this way has been exclusively characterized by a high degree of polarization, excellent directionality, high intensity, and good collimation, which makes it way more qualified in the cases of nuclear physics researches in comparison with gamma rays produced in alternative ways.

3. Comparison

One of the most significant aspects that is required of artificial gamma ray is controllability and accuracy of the its direction. A stable and highly collimated source of gamma-ray is of great importance. For instance, it can be used in advanced experiments in nuclear physics, especially in the identification of subatomic properties of nucleons, where the high accuracy of the emission source is to be guaranteed. Therefore, the influences of experimental errors can be reduced to the largest extent. In addition, the intensity of gamma ray in a particular direction is associated with its directionality.

Different approaches have been taken in the fields of laser-plasma interactions and FEL to attain radiative directionality. The uncertainty for laser-plasma interactions lies in the implosion phase of the gas jet. Though the direction of the incident laser ray can be determined, the resultant ultrahigh electron beams can be scattered into different directions given different implosion parameters, including the density distribution of the inertial confinement fusion material, the density of the resultant plasmas in which the electrons travel etc. Experiments have identified the thickness and radius of the bremsstrahlung converter as two essential factors in determining the divergence of resultant gamma rays, which can be customized given specific optical circumstances and required intensity of the resultant gamma-rays. By reducing the thickness and the radius the converter, the divergence of gamma ray can be controlled, which also limits the peak intensity of the ray. Even though, the collimation of the gamma rays is achieved at the expense of its conversion efficiency, where a negative linear relationship can be inferred with respect to the conversion efficiency, which affects the intensity as a result, and the directionality.

Gamma-rays based on FEL, on the other hand, appear more advantageous compared with the laser-plasma accelerators in the case of collimation. By manipulation of the setting of the two bunches of electrons, the polarization of FEL can be determined and controlled in the first place, and considering the directionality a scattered gamma ray, that it is always orthogonal to the polarized orientation, the direction of gamma ray can be known by inference from that of the electron beam. Besides, the arrangement of undulator in the set-up for FELs, which consists of magnets aligned in a straight line, seems to further ensure the certainty of the electrons' path. However, disturbance to the collimation of the scattered rays can still arise from the collision between the electron beam and the FEL, which, although assumed to be a head-on interaction, may experience diversion given the instability of propagating paths of the input electromagnetic waves, and has high requirements for the accuracy of experimental installations.

4. Conclusion

In summary, both the laser-plasm interaction and the free-electron laser (FEL) appear as well-developed methods to produce artificial gamma rays. Different mechanisms are employed in each of these two approaches as to achieve collimation of the resultant gamma rays. For the laser-plasma interaction, the gas jet plays a significant role, whereby a negative linear relationship can be identified between the intensity of gamma ray in one direction and the conversion efficiency of the ray; the

latter is associated with the thickness and radius of the gas jet. For the FEL, the installation of the undulator is pivotal, in which the bundles of electron are forced to travel through an oscillatory but generally straight path across the storage ring. The directionality of the gamma ray produced in this way can be inferred by taking into consideration the polarization of the free-electron beams. In the future, it is believed that more advanced scenarios will be proposed and realized experimentally. Overall, these results offer a guideline for gamma ray generation based on the state-of-art facilities.

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